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IN THE UNITED STATES PATENT AND TRADEMARK OFFICE

In Re the application of:)
Steve W.L. Yeung, Richard C.H. Lee)
Serial No.: 09/678,058)
Assigned Filing Date: October 2, 2000)
For: AN EFFICIENT LIQUID CRYSTAL DISPLAY DRIVING SCHEME USING ORTHOGONAL BLOCK – CIRCULANT MATRIX)

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Submitted herewith is a document upon which Applicant respectfully requests a convention priority for the above-captioned application, namely United Kingdom Patent Application No. 99 23292.8 filed October 1, 1999.

Respectfully submitted,

BLAKELY, SOKOLOFF, TAYLOR & ZAFMAN

Dated: 3/23/01

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2. Patent application number *(The Patent Office will fill in this part)*	01 OCT 1999 9923292.8
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Patents ADP number *(if you know it)*	
If the applicant is a corporate body, give the country/state of its incorporation	1) BRITISH VIRGIN ISLANDS
4. Title of the invention	AN EFFICIENT LIQUID CRYSTAL DISPLAY DRIVING SCHEME USING ORTHOGONAL BLOCK-CIRCULANT MATRIX
5. Name of your agent *(if you have one)*	
"Address for service" in the United Kingdom to which all correspondence should be sent *(including the postcode)*	EDWARD EVANS & CO CHANCERY HOUSE 53-64 CHANCERY LANE LONDON WC2A 1SD
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AN EFFICIENT LIQUID CRYSTAL DISPLAY DRIVING SCHEME USING ORTHOGONAL BLOCK-CIRCULANT MATRIX

1 Introduction

The present invention relates to a driving scheme of liquid crystal display, and more particularly to a special arrangement of the entries of the driving matrix, which results in an efficient implementation of the scheme and a reduction in hardware complexity.

Passive matrix driving scheme is commonly adopted for driving a liquid crystal display. For those high-mux displays with liquid crystals of fast response, the problem of loss of contrast due to frame response is severe. To cope with this problem, active addressing was proposed in which orthogonal matrix is used as the common driving signal. However, the method suffers from the problem of high computation and memory burden. Even worse, the difference in sequencies of the rows of matrix results in different row signal frequencies. This may results in severe crosstalk problem. On the other hand, Multi-Line-Addressing (MLA) was proposed that makes a compromise between frame response, sequency, and computation problems. The block-diagonal driving matrix is made up of lower order orthogonal matrices. To further suppress the frame response, column interchanges of the driving matrix were suggested in such a way the selections are evenly distributed among the frame. The complexity of the scheme is proportional to square of the order of the building matrix. Increase of order of scheme results in complexity increase in both time and spatial domains. The order increase asks for more logic hardware and voltage levels of the column signal.

In the present invention, a special arrangement of the entries of driving matrix is proposed. By imposing orthogonal block-circulant property to the building blocks of the row (common) driving waveform, the row signals can be made to differ by time shifts only. Each row can now be implemented as a shifted version of preceding rows by using shift registers. The complexity of the matrix driving scheme is greatly reduced and is linearly proportional to the order of the orthogonal block-circulant building block.

2 Liquid Crystal Driving Scheme Using Orthogonal Block-Circulant Matrix

The following shows an order-8 Hadamard matrix.

$$\begin{bmatrix} 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\ 1 & -1 & 1 & -1 & 1 & -1 & 1 & -1 \\ 1 & 1 & -1 & -1 & 1 & 1 & -1 & -1 \\ 1 & -1 & -1 & 1 & 1 & -1 & -1 & 1 \\ 1 & 1 & 1 & 1 & -1 & -1 & -1 & -1 \\ 1 & -1 & 1 & -1 & -1 & 1 & -1 & 1 \\ 1 & 1 & -1 & -1 & -1 & -1 & 1 & 1 \\ 1 & -1 & -1 & 1 & -1 & 1 & 1 & -1 \end{bmatrix}$$

As mentioned in previous section, because of the computation burden and sequency problem of using active driving, MLA was proposed. To implement an 8-way drive by using 4-line MLA, two order-4 Hadamard matrices are used as the diagonal building blocks of the 8x8 driving matrix. The resulting common driving matrix is as follows:

$$\begin{bmatrix} 1 & 1 & 1 & 1 & 0 & 0 & 0 & 0 \\ 1 & -1 & 1 & -1 & 0 & 0 & 0 & 0 \\ 1 & 1 & -1 & -1 & 0 & 0 & 0 & 0 \\ 1 & -1 & -1 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 1 & 1 & 1 \\ 0 & 0 & 0 & 0 & 1 & -1 & 1 & -1 \\ 0 & 0 & 0 & 0 & 1 & 1 & -1 & -1 \\ 0 & 0 & 0 & 0 & 1 & -1 & -1 & 1 \end{bmatrix}$$

To minimize the sequency problem, Hirai [14] proposed another 4x4 orthogonal building block. The resulting row (common) driving matrix is as follows:

$$\begin{bmatrix} -1 & 1 & 1 & 1 & 0 & 0 & 0 & 0 \\ 1 & 1 & -1 & 1 & 0 & 0 & 0 & 0 \\ 1 & -1 & 1 & 1 & 0 & 0 & 0 & 0 \\ 1 & 1 & 1 & -1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & -1 & 1 & 1 & 1 \\ 0 & 0 & 0 & 0 & 1 & 1 & -1 & 1 \\ 0 & 0 & 0 & 0 & 1 & -1 & 1 & 1 \\ 0 & 0 & 0 & 0 & 1 & 1 & 1 & -1 \end{bmatrix}.$$

Notice that a general m-way display will have a mxm block diagonal orthogonal driving matrix made up of $m/4$ (assuming that m is an integer multiple of 4) 4x4 building blocks. Note also that the actual voltage applied is not necessary ± 1 but a constant multiple of the value (i.e., $\pm k$). To further suppress the frame response, Hirai proposed column interchanges of the row (common) driving matrix in such a way that the selections are evenly distributed among the frame. Using the 8-way drive as example, the following row (common) driving matrix is resulted

$$\begin{bmatrix} -1 & 0 & 1 & 0 & 1 & 0 & 1 & 0 \\ 1 & 0 & 1 & 0 & -1 & 0 & 1 & 0 \\ 1 & 0 & -1 & 0 & 1 & 0 & 1 & 0 \\ 1 & 0 & 1 & 0 & 1 & 0 & -1 & 0 \\ 0 & -1 & 0 & 1 & 0 & 1 & 0 & 1 \\ 0 & 1 & 0 & 1 & 0 & -1 & 0 & 1 \\ 0 & 1 & 0 & -1 & 0 & 1 & 0 & 1 \end{bmatrix}$$

In this invention, we propose a method of generating orthogonal block-circulant building blocks that result in reduced hardware complexity of the driving circuitry. First of all, we define orthogonal block-circulant matrix as follows:

Definition: An NMxNM block-circulant matrix B consisting of N MxM building blocks $A_1, A_2, \ldots A_N$ *is of the form*

$$B = \begin{bmatrix} A_1 & A_2 & \Lambda & A_N \\ A_N & A_1 & \Lambda & A_{N-1} \\ \mathrm{M} & \mathrm{M} & \mathrm{O} & \mathrm{M} \\ A_2 & A_3 & A_N & A_1 \end{bmatrix}.$$

It is said to be orthogonal block-circulant if $B^T B = BB^T = (NM) I_{NM}$.

For example, the following 4x4 matrix is orthogonal block-circulant

In this case, N can be 2 or 4. If N=2, then each A_j is 2x2 matrix. If N=4, then each A_j is

$$\begin{bmatrix} -1 & 1 & 1 & 1 \\ 1 & -1 & 1 & 1 \\ 1 & 1 & -1 & 1 \\ 1 & 1 & 1 & -1 \end{bmatrix}$$

a scalar (1 or −1). The orthogonal block-circulant matrix can be used as the diagonal building block of a row (common) driving matrix. By proper column and row interchanges, the resulting driving matrix has a property that each row is a shifted version of preceding rows and can be implemented by using shift registers. The following shows the resulting 8-way drive using 4x4 orthogonal block-circulant matrix after suitable row and column interchanges.

$$\begin{bmatrix} -1 & 0 & 1 & 0 & 1 & 0 & 1 & 0 \\ 0 & -1 & 0 & 1 & 0 & 1 & 0 & 1 \\ 1 & 0 & -1 & 0 & 1 & 0 & 1 & 0 \\ 0 & 1 & 0 & -1 & 0 & 1 & 0 & 1 \\ 1 & 0 & 1 & 0 & -1 & 0 & 1 & 0 \\ 0 & 1 & 0 & 1 & 0 & -1 & 0 & 1 \\ 1 & 0 & 1 & 0 & 1 & 0 & -1 & 0 \\ 0 & 1 & 0 & 1 & 0 & 1 & 0 & -1 \end{bmatrix}$$

For higher order B, the choice of the order of sub-block A_j is limited. Some M might result in nonexistence of orthogonal block-circulant B. Let MN=6, then M, the order of sub-block, can be 1, 2, or 3. It can be shown that orthogonal block-circulant B can be achieved by M=2, 3, but not M=1. In general, given that MN is even, it can be shown that orthogonal block-circulant B always exists provided that M□1. In the following, two means of generating orthogonal block-circulant matrices are proposed.

The first method is based on theory of *paraunitary* matrix but it by no means generates all orthogonal block-circulant matrices. The second method is a means to identify orthogonal block-circulant matrices by nonlinear programming. Theoretically, it can be used to generate all orthogonal block-circulant matrices.

3 Generation of Orthogonal Block-Circulant Matrix Using Paraunitary Matrix

Consider order MxNM sub-matrix of B as follows:

$$E = [A_1 \quad A_2 \quad \Kappa \quad A_N]$$

Define nxn shift matrix $S_{n,m}$ as follows

$$S_{n,m} = \begin{bmatrix} 0 & I_{m\times m} \\ 0_{(n-m)\times(n-m)} & 0 \end{bmatrix}$$

A paraunitary matrix E of order MxNM satisfies

(i) E is orthogonal. i.e.,

$$EE^T = I$$

(ii) E is orthogonal to its column shift by multiples of M. i.e.,

$$ES_{NM,iM}E^T = 0$$

for $i = 1,2, \ldots ,N\text{-}1$.

In general, paraunitary matrices can be represented in a cascade lattice form with rotational angles as parameters. Yeung et al. proposed a new LCD driving scheme based on paraunitary matrices (refer to [16] for details). The following are two example 2x4 paraunitary matrices.

$$E_1 = \begin{bmatrix} 1 & 1 & -1 & 1 \\ -1 & -1 & -1 & 1 \end{bmatrix}$$

$$E_2 = \begin{bmatrix} -1 & 1 & 1 & 1 \\ 1 & -1 & 1 & 1 \end{bmatrix}$$

We have the following property of paraunitary matrices:

Property: B generated by block-circulating paraunitary E is orthogonal.

Proof: Define nxn recurrent shift matrix $R_{n,m}$ as follows

An *orthogonal block-circulant* matrix B of order NMxNM with MxNM sub-matrix E satisfies

(i) E is orthogonal. i.e.,

$$EE^T = I$$

(ii) E is orthogonal to its recurrent shift by multiples of M. i.e.,

$$ER_{NM,iM}E^T = 0$$

for $i = 1,2, \ldots ,N$-1.

Provided that E is paraunitary, as

$$R_{n,m} = S_{n,m} + S^T_{n-m,n-m}$$

we have

$$ER_{(N+1)M,iM}E^T = E(S_{n,m} + S^T_{n-m,n-m})E^T = ES_{n,m}E^T + ES^T_{n-m,n-m}E^T = 0$$

and that completes the proof. Notice that E is paraunitary is a sufficient but not necessary condition for B to be orthogonal block-circulant. Using E_1 and E_2 as building blocks, we obtain the following orthogonal block-circulant matrices.

$$B_1 = \begin{bmatrix} 1 & 1 & -1 & 1 \\ -1 & -1 & -1 & 1 \\ -1 & 1 & 1 & 1 \\ -1 & 1 & -1 & -1 \end{bmatrix}$$

$$B_2 = \begin{bmatrix} -1 & 1 & 1 & 1 \\ 1 & -1 & 1 & 1 \\ 1 & 1 & -1 & 1 \\ 1 & 1 & 1 & -1 \end{bmatrix}$$

Notice that B_2 is orthogonal circulant as well as orthogonal block-circulant. As illustrated before, by using it as the building block of row (common) driving matrix with suitable row and column interchanges, each row is a delay-1 shifted version of preceding row. However, B_1 is orthogonal block-circulant but it is not circulant. By suitable row and column interchanges of the resulting driving matrix, two sets of row (common) driving waveforms are obtained. Within a set, each row is a shifted version of the others. We observe that the complexity of implementation is proportional to the order of the sub-blocks A_j (i.e., M). For NM=4, we observe that M can be 1 or 2. For higher order, M=1 does not result in any circulant B that is orthogonal. Provided M=2, orthogonal block-circulant B always exists and can be generated by 2x2N paraunitary matrices. The driving matrix resulted from B_2 with suitable column interchanges is

shown below:

$$\begin{bmatrix} 1 & 0 & 1 & 0 & -1 & 0 & 1 & 0 \\ -1 & 0 & -1 & 0 & -1 & 0 & 1 & 0 \\ -1 & 0 & 1 & 0 & 1 & 0 & 1 & 0 \\ -1 & 0 & 1 & 0 & -1 & 0 & -1 & 0 \\ 0 & 1 & 0 & 1 & 0 & -1 & 0 & 1 \\ 0 & -1 & 0 & -1 & 0 & -1 & 0 & 1 \\ 0 & -1 & 0 & 1 & 0 & 1 & 0 & 1 \\ 0 & -1 & 0 & 1 & 0 & -1 & 0 & -1 \end{bmatrix}$$

Rows 1, 3, 5, 7 and 2, 4, 6, 8 form the two sets within which each row is a shifted version of the others.

4 Generation of Orthogonal block-circulant Matrix by Nonlinear Programming

We might also generate orthogonal block-circulant matrix by nonlinear programming. We use the method of steepest descent to illustrate the idea. The method of steepest descent is widely used in the identification of complex and nonlinear systems. The update law in identifying sub-matrix E can be stated as follows:

$$E_{n+1} = E_n + \delta \tfrac{\partial P}{\partial E}$$

where□is the step size. P is the cost or penalty function. We set P as follows:

$$P(E) = \sum_{i,j} \left(e_{ij}^2 - 1\right)^2 + \left\|EE^T - I\right\|_F^2 + \sum_i \left\|ER_{NM,iM} E^T\right\|_F^2$$

e_{ij} are the entries of E. □□$_F$ is the Frobenius norm of a matrix. The first summation in the function forces all the entries of E to be ±1. The second one forces E to be orthogonal, while the third summation ensures orthogonal block-circulant property of the resulting B.

5 List of Order-4 and Order-8 Orthogonal Block-Circulant Matrices

The following is an exhaustion of all 2x4 and 2x8 sub-matrices E with entries ±1 that result in orthogonal block-circulant building block.

5.1 Order-4

(1)

$$\begin{bmatrix} 1 & 1 & -1 & 1 \\ 1 & 1 & 1 & -1 \end{bmatrix},$$

(2)

$$\begin{bmatrix} -1 & 1 & 1 & 1 \\ 1 & 1 & 1 & -1 \end{bmatrix};$$

(3)

$$\begin{bmatrix} -1 & 1 & -1 & -1 \\ 1 & 1 & -1 & 1 \end{bmatrix};$$

(4)

$$\begin{bmatrix} -1 & -1 & -1 & 1 \\ 1 & 1 & -1 & 1 \end{bmatrix};$$

(5) all alternatives of (1)-(4) generated by

(i) sign inversion (i.e., $-E$);
(ii) row interchange, i.e.,

$$\begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix} E;$$

(iii) circulant shift of E, i.e.,

$$ER_{4,2}$$

and any combinations of (i)-(iii).

5.2 Order-8

(1)

$$\begin{bmatrix} 1 & 1 & -1 & 1 & 1 & -1 & 1 & 1 \\ 1 & 1 & 1 & -1 & 1 & -1 & -1 & -1 \end{bmatrix};$$

(2)

$$\begin{bmatrix} 1 & 1 & 1 & -1 & 1 & -1 & -1 & -1 \\ \text{[illegible]} \end{bmatrix};$$

$$\begin{bmatrix} \text{[illegible]} \\ 1 & 1 & 1 & 1 & -1 & 1 & 1 & -1 \end{bmatrix};$$

(3)
(4)
(5)
(6)

$$\begin{bmatrix} 1 & 1 & -1 & 1 & -1 & 1 & -1 & -1 \\ \text{[illegible]} \end{bmatrix};$$

$$\text{[illegible]}$$

$$\begin{bmatrix} \text{[illegible]} \\ 1 & 1 & 1 & 1 & -1 & 1 & 1 & -1 \end{bmatrix};$$

(7)

(8)

$$\begin{bmatrix} -1 & 1 & 1 & -1 & 1 & -1 & 1 & -1 \\ 1 & 1 & 1 & 1 & 1 & 1 & -1 & -1 \end{bmatrix};$$

(9)

$$\begin{bmatrix} -1 & 1 & 1 & 1 & 1 & 1 & 1 & -1 \\ 1 & 1 & -1 & 1 & -1 & 1 & -1 & -1 \end{bmatrix};$$

(10)

$$\begin{bmatrix} -1 & 1 & -1 & 1 & -1 & 1 & 1 & -1 \\ 1 & 1 & -1 & -1 & -1 & -1 & -1 & -1 \end{bmatrix};$$

(11)

$$\begin{bmatrix} -1 & 1 & 1 & -1 & -1 & -1 & -1 & -1 \\ 1 & 1 & -1 & 1 & -1 & 1 & -1 & -1 \end{bmatrix};$$

(12)

$$\begin{bmatrix} 1 & -1 & -1 & 1 & -1 & 1 & -1 & 1 \\ 1 & 1 & 1 & 1 & 1 & 1 & -1 & -1 \end{bmatrix};$$

(13)

$$\begin{bmatrix} 1 & -1 & -1 & 1 & 1 & -1 & 1 & -1 \\ 1 & 1 & 1 & 1 & 1 & 1 & -1 & -1 \end{bmatrix};$$

(14)

$$\begin{bmatrix} 1 & -1 & 1 & -1 & 1 & -1 & -1 & 1 \\ 1 & 1 & 1 & 1 & 1 & 1 & -1 & -1 \end{bmatrix};$$

(15)

$$\begin{bmatrix} 1 & -1 & -1 & 1 & -1 & -1 & -1 & -1 \\ 1 & 1 & 1 & -1 & 1 & -1 & -1 & -1 \end{bmatrix};$$

(16)

$$\begin{bmatrix} 1 & -1 & 1 & -1 & 1 & 1 & -1 & -1 \\ 1 & 1 & 1 & 1 & 1 & -1 & -1 & 1 \end{bmatrix};$$

(17)

$$\begin{bmatrix} 1 & -1 & 1 & 1 & 1 & 1 & -1 & 1 \\ 1 & 1 & 1 & -1 & 1 & -1 & -1 & -1 \end{bmatrix};$$

(18)

$$\begin{bmatrix} 1 & 1 & -1 & 1 & 1 & 1 & 1 & -1 \\ -1 & 1 & 1 & 1 & -1 & 1 & -1 & -1 \end{bmatrix};$$

(19)

$$\begin{bmatrix} 1 & 1 & 1 & -1 & 1 & 1 & -1 & 1 \\ -1 & 1 & 1 & 1 & -1 & 1 & -1 & -1 \end{bmatrix};$$

(20)

$$\begin{bmatrix} 1 & 1 & -1 & 1 & 1 & 1 & 1 & -1 \\ 1 & -1 & 1 & 1 & 1 & -1 & -1 & -1 \end{bmatrix};$$

(21)
(22)
(23)
(24)

$$\begin{bmatrix} -1 & 1 & 1 & 1 & 1 & -1 & 1 & 1 \end{bmatrix};$$

[illegible]

$$\begin{bmatrix} -1 & 1 & 1 & 1 & -1 & 1 & -1 & -1 \end{bmatrix},$$

(25)
(26)
(27)

[illegible]

(28) all alternatives of (1)-(27) generated by

(i) sign inversion (i.e., $-E$);
(ii) row interchange, i.e.,

$$\begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix} E;$$

(iii) circulant shift of E, i.e.,

$$ER_{8,2i}$$

i=1, 2, or 3, and any combinations of (i)-(iii)

SUMMARY OF INVENTION

(1) A protocol for driving a liquid crystal display within which the row (common) driving matrix is made up of orthogonal block-circulant matrices.

(2) Following on from (1), the protocol for a liquid crystal display results from row and column interchanges of the row (common) driving matrix mentioned in (1).

(3) Following on from (1), the row (common) driving matrix can be an orthogonal block-circulant matrix.

(4) Following on from (1), the row (common) driving matrix can be a block diagonal matrix wherein all the building blocks are orthogonal block-circulant.

(5) Following on from (2) and/or (4), the row (common) driving matrix can be row and column interchanged version of the row (common) driving matrix mentioned in (4).

(6) In particular, there is provided a driving protocol such that the row (common) driving matrix is based on orthogonal block-circulant building blocks generated by method stated in Section 3.

(7) In particular, there is provided a driving protocol such that the row (common) driving matrix is based on orthogonal block-circulant building blocks generated by method stated in Section 4.

(8) In particular, there is provided a driving protocol such that the row (common) driving matrix is based on order-4 and 8 orthogonal block-circulant building blocks generated by sub-matrices stated in Section 5.1 and 5.2

References

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[2] US Patent No. 5,677,705
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